New Low-energy Leptoquark Interactions

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Abstract

We discuss an extension of the standard model (SM) with vector and scalar leptoquarks. The renormalizable leptoquark Lagrangian consistent with the SM gauge symmetry is presented including the leptoquark-Higgs interactions previously not considered in the literature. We discuss the importance of these new interactions for leptoquark phenomenology. After the electro-weak symmetry breaking they generate non-trivial leptoquark mass matrices. These lead to mixing between different $SU(2)_L$-multiplets of the leptoquarks and induce at low energies new effective 4-fermion lepton-quark vertices. The latter affect the standard leptoquark phenomenology. We discuss constraints on these interactions from the helicity-suppressed $\pi \to \nu + e$ decay.

The interest on leptoquarks (LQ) [1] has been renewed during the last few years since ongoing collider experiments have good prospects for searching these particles [2]. LQs are vector or scalar particles carrying both lepton and baryon numbers and, therefore, have a well distinguished experimental signature.

LQs can be quite naturally introduced in the low-energy theory as a relic of a more fundamental theory at some high-energy scale. In such a way LQs can emerge from grand unified theories (GUT) [3], [4], including the superstring-inspired versions of GUT [4], models of extended technicolour [5]-[6] and composite models [7].

The low-energy LQ phenomenology has received considerable attention. Possible LQ manifestations in various processes have been extensively investigated [2]-[16]. Various constraints on LQ masses and couplings have been deduced from existing experimental data and prospects for the forthcoming experiments have been estimated.

Direct searches of LQs as s-channel resonances in deep inelastic ep-scattering at HERA experiments [17] placed lower limits on their mass $M_{LQ} \geq 140 -$

235GeV [18] depending on the LQ type and couplings. With larger accumulated luminosity HERA will be able to cover almost the whole kinematical region in the LQ masses up to 296 GeV, for couplings to quarks and leptons above 10^{-2}. There are also bounds from other collider experiments. The LEP experiments exclude any LQ lighter then 45 GeV [19], the D0 collaboration rules out LQs lighter than 133 GeV if they couple to the first generation fermions [20], and the CDF collaboration sets a corresponding lower bound at 113 GeV [21].

Dramatic improvements of these constraints are expected in future experiments at pp [8], ep [2], [9], e^+e^- [10],[11] $e\gamma$ [12] and $\gamma\gamma$ [13] colliders.

However, at present the most stringent limits on LQs come from low-energy experiments [14], [15]. Effective 4-fermion interactions, induced by virtual LQ exchange at energies much smaller than their masses, can contribute to atomic parity violation, flavour-changing neutral current (FCNC) processes, meson decays, meson-antimeson mixing and some rare processes. For instance, a typical bound on non-chirally coupled LQs imposed by the helicity-suppressed $\pi \to e\nu$ decay is $M_{LQ}^2/|g_L g_R| \geq (100\mathrm{TeV})^2$, where $g_{L,R}$ are LQ couplings [6].

To consider LQ phenomenology in a model-independent fashion one usually follows some general principles in constructing the Lagrangian of the LQ interactions with the standard model (SM) fields. Generic principles are renormalizability **(p1)** and invariance **(p2)** under the SM gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. In order to obey the stringent constraints from **(c1)** helicity-suppressed $\pi \to e\nu$ decay [6], from **(c2)** FCNC processes [16], [1] and **(c3)** proton stability [16], the following three assumptions are also commonly adopted: **(a1)** LQ couplings are "chiral", i.e. each type of LQs couples either to left-handed or to right-handed quarks only (call them left- and right-type LQ); **(a2)** LQ couplings are generation "diagonal", i.e. they couple only to a single generation of leptons and a single generation of quarks; **(a3)** LQ interactions conserve baryon (B) and lepton (L) numbers.

Of course, if these empirical assumptions (a1)-(a3) really determine the LQ interactions, they have to be explained in terms of an underlying theory predicting light LQs. Such an explanation can be found for instance, within theories with a "horizontal" symmetry [22]. We will show, however, that assumption (a1) does not solve problem (c1) since the LQ couplings with the SM Higgs doublet reintroduce the non-chiral interaction terms. Therefore, to obey (c1) one should not only claim chirality of the LQ-quark couplings (a1) but also absence of some LQ-Higgs couplings. It is unlikely that both requested properties can have the same origin in the underlying theory.

In the following we consider changes in LQ phenomenology caused by the LQ-Higgs interactions. We base our consideration on the general principles (p1),(p2) as well as on the assumptions (a1)-(a3).

In the literature only LQ-lepton-quark interaction terms have been considered. They have the following form [2] for the scalar LQs

$$\begin{aligned}
\mathcal{L}_{S-l-q} &= \lambda^{(R)}_{S_0}\cdot\overline{u^c}P_R e\cdot S_0^{R\dagger}+\lambda^{(R)}_{\tilde{S}_0}\cdot\overline{d^c}P_R e\cdot\tilde{S}_0^{\dagger}+ \\
&+ \lambda^{(R)}_{S_{1/2}}\cdot\overline{u}P_L l\cdot S_{1/2}^{R\dagger}+\lambda^{(R)}_{\tilde{S}_{1/2}}\cdot\overline{d}P_L l\cdot\tilde{S}_{1/2}^{\dagger}+ \\
&+ \lambda^{(L)}_{S_0}\cdot\overline{q^c}P_L i\tau_2 l\cdot S_0^{L\dagger}+\lambda^{(L)}_{S_{1/2}}\cdot\overline{q}P_R i\tau_2 e\cdot S_{1/2}^{L\dagger}+ \\
&+ \lambda^{(L)}_{S_1}\cdot\overline{q^c}P_L i\tau_2\hat{S}_1^{\dagger}l+h.c.
\end{aligned} \tag{1}$$

and for the vector LQs

$$\begin{aligned}
\mathcal{L}_{V-l-q} &= \lambda^{(R)}_{V_0}\cdot\overline{d}\gamma^{\mu}P_R e\cdot V_{0\mu}^{R\dagger}+\lambda^{(R)}_{\tilde{V}_0}\cdot\overline{u}\gamma^{\mu}P_R e\cdot\tilde{V}_{0\mu}^{\dagger}+ \\
&+ \lambda^{(R)}_{V_{1/2}}\cdot\overline{d^c}\gamma^{\mu}P_L l\cdot V_{1/2\mu}^{R\dagger}+\lambda^{(R)}_{\tilde{V}_{1/2}}\cdot\overline{u^c}\gamma^{\mu}P_L l\cdot\tilde{V}_{1/2\mu}^{\dagger}+ \\
&+ \lambda^{(L)}_{V_0}\cdot\overline{q}\gamma^{\mu}P_L l\cdot V_{0\mu}^{L\dagger}+\lambda^{(L)}_{V_{1/2}}\cdot\overline{q^c}\gamma^{\mu}P_R e\cdot V_{1/2\mu}^{L\dagger}+ \\
&+ \lambda^{(L)}_{V_1}\cdot\overline{q}\gamma^{\mu}P_L\hat{V}_{1\mu}^{\dagger}l+h.c.
\end{aligned} \tag{2}$$

Here $P_{L,R}=(1\mp\gamma_5)/2$; q and l are the quark and the lepton doublets; S_i^j and V_i^j are the scalar and vector LQs with the weak isospin i=0, 1/2, 1 coupled to left-handed ($j=L$) or right-handed ($j=R$) quarks respectively. The LQ quantum numbers are listed in Table 1. For LQ triplets $\Phi_1=S_1,V_1^{\mu}$ we use the notation $\hat{\Phi}_1=\vec{\tau}\cdot\vec{\Phi}_1$.

There are no fundamental reasons forbidding LQ interactions with the standard model Higgs doublet H. The most general form of the LQ-Higgs interaction Lagrangian, consistent with (p1) and (p2) can be expressed as

$$\begin{aligned}
\mathcal{L}_{LQ-H} &= h^{(i)}_{S_0}Hi\tau_2\tilde{S}_{1/2}\cdot S_0^i+h^{(i)}_{V_0}Hi\tau_2\tilde{V}^{\mu}_{1/2}\cdot V^i_{0\mu}+ \\
&+ h_{S_1}Hi\tau_2\hat{S}_1\cdot\tilde{S}_{1/2}+h_{V_1}Hi\tau_2\hat{V}_1^{\mu}\cdot\tilde{V}_{1/2\mu}+ \\
&+ Y^{(i)}_{S_{1/2}}\left(Hi\tau_2S^i_{1/2}\right)\cdot\left(\tilde{S}^{\dagger}_{1/2}H\right)+Y^{(i)}_{V_{1/2}}\left(Hi\tau_2V^{\mu(i)}_{1/2}\right)\cdot\left(\tilde{V}^{\dagger}_{1/2\mu}H\right)+ \\
&+ Y_{S_1}\left(Hi\tau_2\hat{S}_1^{\dagger}H\right)\cdot\tilde{S}_0+Y_{V_1}\left(Hi\tau_2\hat{V}^{\dagger}_{1\mu}H\right)\cdot\tilde{V}_0^{\mu}+ \\
&+ \kappa^{(i)}_S\left(H^{\dagger}\hat{S}_1H\right)\cdot S_0^{i\dagger}+\kappa^{(i)}_V\left(H^{\dagger}\hat{V}_1^{\mu}H\right)\cdot V^{i\dagger}_{0\mu}+h.c.- \\
&- \left(\eta_{\Phi}M_{\Phi}^2-g_{\Phi}^{(i_1i_2)}H^{\dagger}H\right)\Phi^{i_1\dagger}\Phi^{i_2}.
\end{aligned} \tag{3}$$

Table 1: The Standard model assignments of the scalar S and vector V_μ leptoquarks (LQ). ($Y = 2(Q_{em} - T_3)$)

LQ	$SU(3)_c$	$SU(2)_L$	Y	Q_{em}
S_0	**3**	**1**	-2/3	-1/3
$\tilde{S}_0$	**3**	**1**	-8/3	-4/3
$S_{1/2}$	$\mathbf{3}^*$	**2**	-7/3	(-2/3, -5/3)
$\tilde{S}_{1/2}$	$\mathbf{3}^*$	**2**	-1/3	(1/3, -2/3)
S_1	**3**	**3**	-2/3	(2/3, -1/3,-4/3)
V_0	$\mathbf{3}^*$	**1**	-4/3	-2/3
$\tilde{V}_0$	$\mathbf{3}^*$	**1**	-10/3	-5/3
$V_{1/2}$	**3**	**2**	-5/3	(-1/3, -4/3)
$\tilde{V}_{1/2}$	**3**	**2**	1/3	(2/3, -1/3)
V_1	$\mathbf{3}^*$	**3**	-4/3	(1/3, -2/3,-5/3)

Here $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ is the SM $SU(2)_L$-doublet Higgs field.

Φ^i is a cumulative notation for all leptoquark fields with $i = L, R$ (the same for $i_{1,2}$). We included diagonal mass terms $\eta_\Phi M_\Phi^2 \Phi^\dagger \Phi$ of the scalar ($\eta_S = 1$) and the vector ($\eta_V = -1$) LQ fields. These terms can be generated by spontaneous breaking of the underlying symmetry down to the electro-weak gauge group at some high-energy scale.

The subsequent electro-weak symmetry breaking at the Fermi scale produces additional non-diagonal LQ mass terms leading to non-trivial mixing between LQs from different $SU(2)_L$ multiplets as well as between left- and right-types of LQs, discussed above.

The relevant LQ mass matrices can be read off from eq. (3).

There are 8 non-diagonal LQ mass matrices squared (I=S,V):

$$\mathcal{M}_I^2(Q_I^{(1)}) \;=\; \eta_I \cdot \begin{pmatrix} \eta_I \bar{M}^2_{I_0^L} & g_{I_0}^{LR}|v|^2 & h_{I_0}^{(L)} v & \kappa_I^{(L)}|v|^2 \\ g_{I_0}^{LR}|v|^2 & \eta_I \bar{M}^2_{I_0^R} & h_{I_0}^{(R)} v & \kappa_I^{(R)}|v|^2 \\ h_{I_0}^{(L)} v & h_{I_0}^{(R)} v & \eta_I \bar{M}^2_{\tilde{I}_{1/2}} & h_{I_1} v \\ \kappa_I^{(L)}|v|^2 & \kappa_I^{(R)}|v|^2 & h_{I_1} v & \eta_I \bar{M}^2_{I_1} \end{pmatrix}, \tag{4}$$

$$\mathcal{M}_I^2(Q_I^{(2)}) = \eta_I\cdot\begin{pmatrix} \eta_I\bar{M}^2_{\tilde{I}_{1/2}} & Y^L_{I_{1/2}}v^2 & Y^R_{I_{1/2}}v^2 & \sqrt{2}h_{I_1}v \\ Y^L_{I_{1/2}}v^2 & \eta_I\bar{M}^2_{I^L_{1/2}} & g^{(LR)}_{I_{1/2}}|v|^2 & 0 \\ Y^R_{I_{1/2}}v^2 & g^{(LR)}_{I_{1/2}}|v|^2 & \eta_I\bar{M}^2_{I^R_{1/2}} & 0 \\ \sqrt{2}h_{I_1}v & 0 & 0 & \eta_I\bar{M}^2_{I_1} \end{pmatrix}, \quad (5)$$

$$\mathcal{M}_I^2(Q_I^{(3)}) = \eta_I\cdot\begin{pmatrix} \eta_I\bar{M}^2_{\tilde{I}_0} & \sqrt{2}Y_{I_1}v^2 \\ \sqrt{2}Y_{I_1}v^2 & \eta_I\bar{M}^2_{I_1} \end{pmatrix}, \quad (6)$$

$$\mathcal{M}_I^2(Q_I^{(4)}) = \eta_I\cdot\begin{pmatrix} \eta_I\bar{M}^2_{I^L_{1/2}} & -g^{(LR)}_{I_{1/2}}|v|^2 \\ -g^{(LR)}_{I_{1/2}}|v|^2 & \eta_I\bar{M}^2_{I^R_{1/2}} \end{pmatrix}, \quad (7)$$

where $\bar{M}_I^2 = M_I^2 + \eta_I g_I|v|^2$ is the "shifted" diagonal mass, $v^2 =< H^0 >^2 = (2\sqrt{2}G_F)^{-1}$ is the SM Higgs field vacuum expectation value, G_F is the Fermi constant and $\eta_{S,V} = 1, -1$. The cumulative notation $\mathcal{M}_I^2(Q_I^{(k)})$ encodes the mass matrices squared for the scalar (I=S) and vector ($I = V_\mu$) LQs with electric charges $Q_S^{(1)} = Q_V^{(2)} = -1/3$, $Q_S^{(2)} = Q_V^{(1)} = -2/3$, $Q_S^{(3)} = Q_V^{(4)} = -4/3$, $Q_V^{(3)} = Q_S^{(4)} = -5/3$ in the interaction eigenstate basises: (k=1) $I(Q_I^{(1)}) = (I_0^L, I_0^R, \tilde{I}^\dagger_{1/2}, I_1)$; (k=2) $I(Q_I^{(2)}) = (\tilde{I}_{1/2}, I^L_{1/2}, I^R_{1/2}, I_1^\dagger)$; (k=3) $I(Q_I^{(3)}) = (\tilde{I}_0, I_1)$; (k=4) $I(Q_I^{(4)}) = (I^L_{1/2}, I^R_{1/2})$. Thus, there is a non-trivial mixing of LQs from different $SU(2)_L$ multiplets as well as the $I^L - I^R$ mixing. The latter spoils chirality of the LQ-quark-lepton couplings (a1) and leads to reappearance of the problem with the constraint (c1).

The mass matrices of all other LQ fields remain diagonal after electro-weak symmetry breaking.

To obtain observable predictions from the LQ-lepton-quark interaction Lagrangian in eqs. (1)-(2), fields with non-diagonal mass matrices have to be rotated to the mass eigenstate basis I'. This can be done in the standard way

$$I(Q) = \mathcal{N}^{(I)}(Q)\cdot I'(Q) \quad (8)$$

where $\mathcal{N}^{(I)}(Q)$ are orthogonal matrices such that $\mathcal{N}^{(I)T}(Q_I)\cdot\mathcal{M}_I^2(Q)\cdot\mathcal{N}^{(I)}(Q) = Diag\{M^2_{I_n}\}$ with the M_{I_n} being the mass of the relevant mass eigenstate field I'. All phenomenological consequences of the LQ interactions in eqs. (1)-(3) should be derived in terms of these fields I'.

In this letter we concentrate on the LQ induced 4-fermion lepton-quark effective interactions. For their derivation one has to substitute the expression (8) to eqs. (1)-(2) and "integrate out" heavy LQ fields I'. For vanishing LQ-Higgs couplings (eq. (3)) these interaction terms are listed in ref. [14]. Mixing

between different $SU(2)_L$ multiplets of LQs leads to new terms, vanishing in the limiting case of decoupled LQ and Higgs sectors. Below we list only those new terms which can be most stringently restricted from low-energy processes[1]. After Fierz rearrangement they take the form

$$\begin{aligned}
\mathcal{L}^{eff}_{mix} &= (\bar{\nu} P_R e^c)\left[\frac{\epsilon_S}{M_S^2}(\bar{u}P_R d) + \frac{\epsilon_V}{M_V^2}(\bar{u}P_L d)\right] + (\overline{\nu^c} P_L e^c)\left[\frac{\omega_S}{M_S^2}(\bar{u}P_L d) + \frac{\omega_V}{M_V^2}(\bar{u}P_R d)\right] \\
&- (\bar{\nu}\gamma^\mu P_L e^c)\left[\left(\frac{\alpha_S^{(R)}}{M_S^2} + \frac{\alpha_V^{(R)}}{M_V^2}\right)(\bar{u}\gamma_\mu P_R d) - \sqrt{2}\left(\frac{\alpha_S^{(L)}}{M_S^2} + \frac{\alpha_V^{(L)}}{M_V^2}\right)(\bar{u}\gamma_\mu P_L d)\right], \quad (9)
\end{aligned}$$

where

$$\begin{aligned}
\epsilon_I &= 2^{-\eta_I}\left[\lambda^{(L)}_{I_1}\lambda^{(R)}_{\tilde{I}_{1/2}}\left(\theta^I_{43}(Q_I^{(1)}) + \eta_I\sqrt{2}\theta^I_{41}(Q_I^{(2)})\right) - \lambda^{(L)}_{I_0}\lambda^{(R)}_{\tilde{I}_{1/2}}\theta^I_{13}(Q_I^{(1)})\right], \\
\omega_I &= 2^{-\eta_I}\left[\lambda^{(L)}_{I_0}\lambda^{(R)}_{I_0}\theta^I_{12}(Q_I^{(1)}) + \lambda^{(R)}_{I_0}\lambda^{(L)}_{I_1}\theta^I_{42}(Q_I^{(1)}) + \lambda^{(L)}_{I_{1/2}}\lambda^{(R)}_{I_{1/2}}\theta^I_{32}(Q_I^{(2)})\right], \\
\alpha_I^{(L)} &= \frac{2}{3+\eta_I}\lambda^{(L)}_{I_{1/2}}\lambda^{(L)}_{I_1}\theta^I_{24}(Q_I^{(2)}), \quad \alpha_I^{(R)} = \frac{2}{3+\eta_I}\lambda^{(R)}_{I_0}\lambda^{(R)}_{\tilde{I}_{1/2}}\theta^I_{23}(Q_I^{(1)}). \qquad (10)
\end{aligned}$$

Here we introduced a mixing parameter

$$\theta^I_{kn}(Q) = \sum_l \mathcal{N}^{(I)}_{kl}(Q)\mathcal{N}^{(I)}_{nl}(Q)\left(\frac{M_I}{M_{I_l}(Q)}\right)^2, \qquad (11)$$

where $Q = -1/3, -2/3$ and $I = S, V$. Common mass scales M_S of scalar and M_V of vector LQs were introduced for convenience.

The interaction terms eq. (9) contribute to various low-energy processes. Using existing experimental data one can obtain constraints on the relevant coupling constants. Here we are not going to discuss this subject in detail but rather present only the most stringent bounds from the helicity-suppressed decay $\pi \to e\nu$. This process is especially sensitive to the first two scalar-pseudoscalar terms leading to a helicity-unsuppressed amplitude. Assuming no spurious cancellations between different contributions we derive on the basis of ref. [14] the following severe constraints:

$$\epsilon_I, \omega_I \leq 5\times 10^{-7}\left(\frac{M_I}{100\text{GeV}}\right)^2 \qquad (12)$$

[1] A detailed study of phenomenological implications of the LQ-Higgs couplings in eq. (3) will be given elsewhere.

Other couplings in eq. (9) are much weaker constrained by low-energy processes previously considered in connection with the LQ phenomenology [14], [15]. We expect that new stringent constraints on LQ couplings can be derived from neutrinoless double beta decay ($0\nu\beta\beta$). The first and the last terms with ϵ, α couplings in eq. (9) contribute to this exotic process within the conventional mechanism based on Majorana neutrino exchange between decaying nucleons. Because of the specific helicity structure the corresponding amplitude acquires an enormously large enhancement factor $p_F/m_\nu \sim 10^8$ ($p_F \approx 100$MeV is the Fermi momentum and m_ν is the neutrino mass) compared to the standard charged current contribution. As a result non-observation of $0\nu\beta\beta$-decay casts stringent constraints on the LQ parameters. This subject will be considered in a separate paper.

In conclusion, we have pointed out that the interactions of leptoquarks with the standard model Higgs field modify low-energy leptoquark phenomenology. They generate new 4-fermion lepton-quark couplings which contribute to various low-energy processes. We have considered as an example the helicity-suppressed $\pi \to e\nu$ decay, which stringently constraints special combinations of the leptoquark couplings including couplings to the Higgs field (see eq. (12)). We stress that an underlying high-energy scale theory containing light leptoquarks must explain not only the chirality of leptoquark couplings to quarks and leptons (see (a1) at the beginning) but also the absence (or smallness) of at least those leptoquark-Higgs couplings which are suppressed by the constraints in eq. (12).

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